

# Circul8: Supporting Circularity Decision Making with a Component-based Real-Time Monitoring Tool for IT Asset Management

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## Abstract

*Harmful chemicals and metals from e-waste affects our environment and human health. The UK produced 24.9kg e-waste per person in 2016, 10kg more than the EU average. A typical laptop manufacturing produces 331kg of CO2 emissions. Early routine maintenance typically extends the use cycle of 3 to 5-year-old computers to at least 9 years. While circular economy (CE) frameworks present a promising approach to reducing this environmental burden, putting circularity into practice remains a significant challenge. A barrier to repairing and reusing electronic products is the lack of information and efficient decision systems to allow people to make informed choices. This paper introduces Circul8, a real-time monitoring and analytics tool designed to enhance data-driven circular asset management. Developed through a Knowledge Transfer Partnership (KTP) between the University of Hull and Techbuyer UK Ltd, Circul8 continuously collects non-intrusive telemetry data from core hardware components, including CPU, memory, storage, and battery usage. The platform features a lightweight agent for data collection, secure MQTT-based data transmission, a time-series analytics backend, and an interactive dashboard for visualising trends and detecting anomalies. Deployed across 70 laptop devices, Circul8 demonstrated its ability to identify performance degradation, thermal anomalies, and component stress—empowering timely and cost-effective maintenance decisions. The tool's open-source release further promotes replicability and cross-sector adoption, embodying co-creation principles and open innovation in sustainable IT.*

**Keywords** – Circul8, Circular Economy (CE), Waste Electrical and Electronic Equipment (WEEE), ICT, CRM

## I. Introduction

The volume of electronic waste (e-waste) is increasing at a pace five times faster than formal recycling efforts, according to a 2024 [report](#) by the United Nations (UN). In 2022 alone, global e-waste reached an unprecedented 62 million tonnes. As digital technologies become more embedded in daily life, both personally and professionally, the rate at which devices are replaced continues to rise. In the United Kingdom (UK), per capita e-waste generation has reached nearly 25 kilograms in recent years, significantly exceeding the European Union (EU) average ([Statista, 2022](#)). The environmental impact is considerable: manufacturing a typical laptop emits around 331 kg of CO<sub>2</sub> and involves in the extraction of rare earth elements and hazardous materials involved in production [1, 2]. In 2023, the [European Union](#) updated its Critical Raw Materials (CRMs) list to include 34 essential resources. Many of these—like cobalt, palladium, platinum, neodymium, praseodymium, dysprosium, antimony, yttrium, indium, tantalum, nickel, copper, and manganese—can be found in laptops. While the Waste Electrical and Electronic Equipment (WEEE) Directive, along with UK regulations, requires that between 65% and 85% of electronic products placed on the market should be recycled, the reality is that recycling efforts tend to focus on the most common and bulky materials, such as plastics and steel. As a result, these valuable critical raw materials often go unrecovered [2]. Although new recycling technologies targeting these rare materials are being developed, they aren't widely available. For now, the most effective way to conserve these materials is to make our electronic devices last longer, keeping them in use for as long as possible before replacing them. This

unsustainable trend highlights the urgent need for a paradigm shift in how we manage the lifecycle of electronic products. The Circular Economy (CE) provides a viable alternative to the traditional take-make-dispose model by promoting the extension of product lifespans through reuse, refurbishment, remanufacturing, and responsible recycling. However, implementing CE principles in the context of consumer electronics, particularly laptops, poses significant challenges. One major barrier is the lack of advanced real-time tools to monitor and manage IT assets effectively. Most existing solutions treat laptops as single, monolithic systems instead of recognising that individual components have different degradation patterns, performance metrics, and economic values [3]. Without detailed insights at the component level, repair and reuse decisions often rely on limited or outdated information, leading to premature disposal of devices and inefficient use of resources [4].

Our work advocates for a more nuanced approach to device monitoring, viewing laptops not as black boxes but as systems made up of multiple interdependent components, each with its own lifecycle. By implementing component-level monitoring, we can generate detailed health scores and predict the device's remaining useful life (RUL) and its individual parts. This approach empowers asset managers and users to make informed decisions regarding circularity, whether that involves upgrading a specific module, initiating proactive maintenance, or retiring a component for reuse elsewhere [5]. This research is part of a Knowledge Transfer Partnership (KTP) between the University of Hull and Techbuyer Limited, a UK-based company specialising in sustainable IT asset management. The project aims to develop an AI-driven, real-time Decision Support System (DSS) for monitoring laptop performance at the component level. The DSS can predict hardware degradation and recommend environmentally friendly and economically viable actions. It enables IT teams in the market to plan budgets and refresh cycles based on performance data rather than the traditional 3-year cycle, which is prone to economic and environmental wastage.

It also has use cases in developing the circular economy in the wider market. Its ability to gather accurate data on items to be refurbished and processed for sale on the secondary market, where a warranty from the refurbishers backs them, de-risks the warranty process by allowing the replacement of weaker components, resulting in fewer returns. The application could also be integrated into the device as a service contract, facilitating another circular economy model. This paper presents the DSS's first and most important part: a component-level monitoring tool, Circul8. We present the conceptual-to-practical framework, system architecture, development methodology, and early deployment outcomes of Circul8. The research addresses various technical and operational challenges, including creating a lightweight, privacy-aware, and secure application and integrating real-time data into multi-criteria decision-making models that can balance cost, performance, and sustainability. The study conducted with the tool highlights tangible and scalable pathways to reduce e-waste, extend device lifespans, and promote data-driven circularity in consumer electronics. In particular, we outline how a tool like Circul8 can form part of a full-scale DSS in our future work. This work can be expanded within the DSS to integrate predictive health scoring and Remaining Useful Life (RUL) modelling, develop behavioural nudging

mechanisms, expand cross-platform compatibility, and assess the long-term environmental impact.

## II. Literature review

### A. Understanding Circular Economy in Electronics: From Theory to Decisions

The Circular Economy has emerged as a transformative framework for rethinking production and consumption systems, shifting away from the traditional linear model of “take, make, dispose” toward strategies that emphasise product longevity, resource efficiency, and waste minimisation [6, 7]. In the context of electronic devices, which are often composed of rare and hazardous materials and experience rapid obsolescence, the CE offers a particularly valuable lens through which to address the dual challenges of environmental degradation and resource scarcity [8, 9]. Consumer electronics—especially laptops, smartphones, and tablets—pose significant environmental and economic concerns. A typical laptop, for instance, generates over 300 kg of CO<sub>2</sub> during its lifecycle and contains components that are difficult to recover or recycle [1]. Despite growing awareness, the global volume of e-waste reached a record 53.6 million metric tonnes in 2019, with only 17.4% documented as formally collected and recycled [10]. Against this backdrop, circular strategies such as reuse, repair, refurbishment, remanufacturing, and recycling have been promoted as practical interventions. However, translating CE theory into practice within the ICT sector remains fraught with technical, behavioural, and organisational barriers [3, 11, 12].

At the heart of CE theory is the principle of retaining the value of products, materials, and components for as long as possible within the economic system [13]. This requires robust frameworks for electronic devices that support decision-making around when and how to repair, reuse, upgrade, or recycle products. Scholars have argued that CE implementation in the ICT domain must be informed by product-service system (PSS) thinking, lifecycle assessment (LCA), and systems-level design that enables modularity, maintainability, and traceability [14]. The literature proposes various CE-related decision-making frameworks. Building on these foundational approaches, Den Hollander [15], for instance, recommend a product-level framework that focuses on the functionality and independence of components. This approach allows for tailored circular strategies considering whether individual parts, like a battery or SSD, can be independently upgraded, reused, or recycled. Meanwhile, the ReSOLVE framework developed by the Ellen MacArthur Foundation outlines a more systemic heuristic, identifying six action areas: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange [16]. Although not exclusive to electronics, the ReSOLVE framework provides valuable conceptual guidance on how value can be retained or restored throughout a product's lifecycle.

Despite these theoretical advances, operationalising CE within the fast-moving consumer electronics market remains a significant challenge. An emerging theme in the literature is what could be termed “intelligent circularity”—the use of digital tools, real-time monitoring, and predictive analytics to inform lifecycle decisions at the component level. Rather than relying on periodic inspections or user-reported faults, intelligent systems can continuously assess performance, degradation, and usage patterns to generate more accurate insights that are context-sensitive [5, 17].

This shift toward data-driven circularity reflects broader technological trends in areas such as predictive maintenance, Industry 4.0, and the Internet of Things (IoT). When applied to electronics, these approaches enable the estimation of the Remaining Useful Life (RUL) of components using machine learning models, which allows for proactive maintenance or replacement strategies well before catastrophic failure occurs. Furthermore, real-time component monitoring opens up new possibilities for circularity beyond mere recycling, such as refurbishing a device by selectively replacing worn-out parts while retaining functional components.

### *B. Current Practices and Tools for Circularity in Electronics*

While the CE concept is well-defined in academic and policy literature, its practical implementation within the electronics sector remains inconsistent and limited, especially for consumer devices. This section critically examines how CE principles have been translated into industry practices, lifecycle management models, and digital tools. It addresses enterprise-level initiatives emerging technologies and analyses shortcomings hindering scalable and sustainable adoption.

#### *a. Industry Initiatives and Lifecycle Management Models*

Regulatory pressures, brand reputation concerns, and evolving consumer expectations have primarily driven efforts to operationalise circularity in electronics. Extended Producer Responsibility (EPR) is a key instrument in this process, a policy approach that holds manufacturers accountable for the end-of-life treatment of their products. Countries within the European Union, Canada, Japan, and parts of the U.S. have incorporated EPR into legislation, mandating take-back schemes, recycling targets, and material disclosure requirements [18, 19]. In response to this policy landscape, several major original equipment manufacturers (OEMs)—notably Apple, Dell, and HP—have launched initiatives such as refurbishment programs, trade-in schemes, and material recovery systems. For example, Apple’s Trade-In and Certified Refurbished programs allow customers to return old devices in exchange for credit and purchase reconditioned products at a lower price. Similarly, Dell’s Asset Recovery Services and HP’s Device Lifecycle Services offer models for managing device returns and extending lifespans through repair and resale. However, as highlighted by Mathur [20], these initiatives primarily focus on the end-of-life (EoL) stage rather than engaging with the full lifecycle of the product—particularly during critical middle phases when proactive maintenance or component upgrades could yield better environmental and economic outcomes.

In the business-to-business (B2B) segment, companies increasingly utilise IT Asset Disposition (ITAD) services. These organisations provide secure data erasure, value assessment, component harvesting, and ethical recycling of corporate IT assets [21]. Companies like Techbuyer, Sims Lifecycle Services, and ERI exemplify this growing market, aligning well with CE goals, especially for enterprise-scale electronics, where controlled lifecycle management is easier to implement. However, the consumer electronics sector, including laptops used in

homes or small businesses, remains noticeably less mature in its circularity practices due to fragmentation, user diversity, and a lack of accessible diagnostic tools. While EPR and ITAD frameworks establish pathways for post-use circularity, they do not adequately address the issue of premature obsolescence—a phenomenon extensively documented in academic research. Studies by [22] and [23] show that many laptops are disposed of not because of hardware failure but due to perceived performance degradation, software slowdowns, or declining battery life. These perceptions—sometimes worsened by planned obsolescence or contradictions in software updates—can lead to the early retirement of otherwise functional devices. This results in significant environmental losses in e-waste and the embedded energy and materials used during the initial manufacturing process. As George [24] point out, current information asymmetries between manufacturers and consumers inhibit circular behaviour. OEMs often restrict access to repair manuals, firmware diagnostics, or even physical access to components, undermining the potential for a broader repair and reuse ecosystem. The Right to Repair movement, gaining traction in both policy and advocacy circles, seeks to counteract these restrictions. However, circularity will remain constrained at scale until such rights are universally enforced and supported with the necessary tools [25].

Remarkably, many of these devices could remain viable for several additional years if users had access to reliable diagnostics, predictive maintenance insights, or upgrade guidance. For instance, replacing a battery or upgrading RAM could alleviate performance concerns and postpone the need for replacement. However, these decisions require component-level visibility—something that is rarely available to end-users or even many IT professionals without specialised tools. Furthermore, the technical knowledge gap is a significant barrier. Even when devices are theoretically repairable, many users lack the confidence, tools, or information to make effective decisions about repairs or upgrades [26]. This creates a paradox where repairable products are disposed of simply because the system lacks a user-centric, intelligence-driven interface that translates technical diagnostics into actionable insights.

#### *b. Existing Tools and Technologies*

Several tools are currently available to support the monitoring and management of electronic assets, as outlined in Table I. However, this research has identified a notable gap in the existing landscape: there is no tool that enables cross-brand, real-time monitoring of components combined with AI-driven decision support for circularity. Most existing solutions operate at the system level and require significant manual input. Moreover, they are not explicitly designed to support refurbishment or maintenance decisions in a user-friendly and scalable way for businesses.

#### *C. Limitations of Existing Approaches and Need for Innovation*

The limitations of current tools are threefold: lack of component-level insight, absence of real-time monitoring, and inability to offer actionable, circularity-driven recommendations.

TABLE I. Comparison of Existing Tools and Platforms for Supporting Circularity in Electronics

Tool/Platform	Purpose	Strengths	Limitations
Nexthink	Endpoint experience analytics (UX, IT Ops)	Strong UX metrics, integrations, and dashboards	Not designed for component reuse decisions or granular diagnostics
IE Tachyon	Real-time IT automation and visibility	Real-time control, security-focused	Lacks emphasis on sustainable IT or refurbishment use cases
Lakeside SysTrack	Digital experience and asset performance	Rich telemetry supports some health-scoring	Heavily geared towards large-scale enterprise IT, complex and expensive
OEM Diagnostic Tools (e.g., Dell SupportAssist, Lenovo Vantage)	Device-level support tools for end-users	Native hardware access, vendor-specific tuning	Proprietary, limited to specific brands, lacking standardisation or reuse orientation
Libre Hardware Monitor / Open Hardware Monitor	Open-source real-time system stats	Lightweight and extensible	No aggregation, alerting, decision support, or security framework
Ereuse.org	Circular economy platforms for ICT reuse	Open-source, community-led, with a focus on traceability	Minimal real-time diagnostics; more focused on asset inventory and ownership traceability

**First**, most monitoring systems treat laptops as single units, overlooking the fact that their components—such as the SSD, CPU, RAM, battery, and motherboard—degrade at different rates and have varying reuse values. Research by Pincioli [27] shows that batteries and SSDs often fail earlier than other components, and replacing them can significantly extend the device’s life by several years. However, without detailed data, these parts are often discarded along with functional components.

**Second**, most diagnostic tools’ static or snapshot-based nature makes them unsuitable for lifecycle tracking or predictive maintenance. Molęda [28] noted that the lack of continuous monitoring prevents organisations from identifying early signs of failure or planning cost-effective repairs. Real-time monitoring, facilitated by lightweight embedded applications, could provide the ongoing data stream necessary for predictive analytics.

**Third**, decision support processes remain primarily manual and qualitative. Even in organisations prioritising sustainability, decisions regarding whether to reuse, recycle, or dispose of devices are often based on heuristic judgments or manufacturer recommendations [29]. Currently, there is a lack of AI-based systems that can integrate real-time health data, cost models, and circular economy (CE) metrics into an ensemble-based classifier or fuzzy multi-criteria decision support system.

The work presented in this paper represents a foundational step towards the development of a decision support system for enabling circular economy decisions in digital infrastructure. As a part of this framework, Circul8 establishes the critical capability of a real-time, component-level monitoring tool that collects granular telemetry data via an embedded privacy-conscious approach that prioritises local processing and user control, aligning with the principles of responsible AI. By focusing on the first building block, Circul8 addresses the ongoing visibility gap

in IT asset management. This applies the foundation for future integration of predictive analytics, health scoring and automated recommendations for circular economy decisions. Consequently, this research provides technical artefacts and a practical pathway for enhancing data-driven sustainability in IT operations.

#### D. Summary and Research Gaps

The literature reveals that while the Circular Economy has become a central theme in sustainability research and policy, its application to consumer electronics remains fragmented. Most existing tools do not offer the level of granularity, intelligence, or usability required to support true circularity at the component level. Moreover, real-world implementations remain rare despite theoretical models advocating for intelligent, data-driven decision support.

The research project responds directly to these research questions (RQs) by developing a decision-support tool:

- **RQ1:** How can a real-time, component-level monitoring tool be designed and implemented to support data-driven circularity decisions for laptops in the ICT sector?
- **RQ2:** In what ways does the proposed monitoring tool address the limitations of current industry practices and existing tools in enabling circular economy outcomes for electronic devices?

It bridges theory and implementation and—crucially—offers a model for how CE principles can be made actionable through intelligent systems design.

### III. Framework and Implementation

#### A. Circul8: System Vision and Design Principles

At the core of this research is **Circul8** - a specially designed, real-time, component-level monitoring system aimed at supporting sustainable IT asset management following the principles of the CE. Circul8 addresses one of the most pressing sustainability challenges: the increasing volume of electronic waste (e-waste), which

results from premature device disposal and a lack of visibility into device health [10, 30].

Modern IT environments often lack transparency regarding laptops' performance and internal components over time. This lack of visibility makes proactive maintenance difficult and undermines the ability to make informed decisions about reuse, refurbishment, or responsible recycling. Circul8 addresses this transparency gap by:

- Continuously monitoring critical components such as CPU, memory, disk, and battery health.
- Logging historical data and offering real-time anomaly detection.
- Visual dashboards are provided to support diagnostics and decision-making.
- Establishing foundational analytics to assist with advanced circularity decisions, including component-level health scoring.

In its complete form, Circul8 includes the following subsystems:

- Lightweight desktop agents deployed on laptops (open-sourced to encourage adoption and transparency).

- A secure cloud server for data aggregation, analytics, and long-term storage.
- A dashboard interface that provides intuitive access to real-time and historical system insights.

This modular, privacy-aware, and scalable architecture allows Circul8 to function as a monitoring tool and provides a foundation for intelligent, circular decision-making within organisations.

### B. Core Functional Components and System Architecture of Circul8

Circul8 is a real-time monitoring and analytics tool purpose-built to support data-driven circularity decisions for laptops within the context of sustainable IT asset management, as shown in Fig. 1. By enabling continuous observation, analysis, and visualisation of performance data at the component level, Circul8 empowers IT teams and organisations to make timely, informed interventions throughout a device's lifecycle—extending its operational life and reducing electronic waste. This section presents a comprehensive overview of the tool's modular architecture, key technical components, and the interdependencies that underpin its functionality.

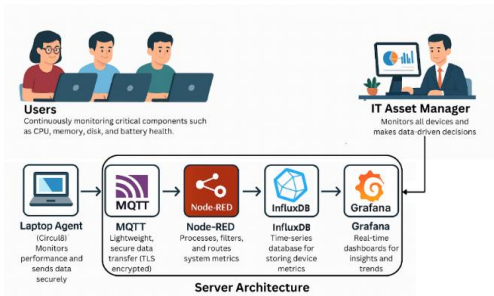


Fig. 1. End-to-End Architecture of the Circul8 Monitoring Tool for Component-Level Data Collection and Visualisation

#### a. Core System Architecture

The tool's system architecture consists of:

- A lightweight Windows-based agent deployed on end-user laptops to capture component-level telemetry in real-time.
- A secure MQTT-based communication layer facilitates efficient, real-time data transmission between the device agents and the cloud backend.
- A cloud-based data collector integrated with a time-series database (InfluxDB) for efficient aggregation, storage, and querying of high-frequency telemetry data.
- An intuitive web-based dashboard for visualising device health and performance trends and detecting anomalies in real-time.

This streamlined pipeline ensures minimal overhead on the host device while enabling robust, scalable data aggregation and analytics.

#### Data Collection Agent

The data collection agent is a lightweight application developed in C#. It acts as the system's core by capturing telemetry from key hardware components, such as CPU

utilisation, disk activity, memory usage, and battery health, at 3-second intervals. Initially, our goal was to monitor more detailed metrics, including CPU power draw, fan speed, battery temperature, and voltage fluctuations, which are essential for accurate diagnostics and predictive modelling. However, accessing these metrics required low-level drivers (e.g., WinRing0), which led to antivirus alerts and compatibility issues in enterprise environments. We shifted to a driverless, WMI-based approach to address this, focusing on informative and consistently available metrics across various devices. This involved selecting parameters that balanced diagnostic value and deployment stability. To ensure resilience, the agent includes local caching and adaptive sampling, allowing data collection to continue during network disruptions or in bandwidth-constrained systems. This practical compromise guarantees reliable, secure, scalable telemetry collection across diverse IT environments.

#### Real-Time Monitoring and Anomaly Detection

In addition to data collection, the agent validates data on-device and performs embedded anomaly detection. It uses established methodologies to flag unusual behaviour patterns—such as sudden temperature spikes or erratic

memory consumption—by dynamically comparing real-time readings to set thresholds. These local checks provide immediate feedback and alerts, reducing reliance on constant cloud connectivity.

### Secure Communication Protocol

Telemetry data is transmitted to the cloud infrastructure using the MQTT protocol, which is known for its lightweight footprint and efficiency in IoT systems. All data transmissions are encrypted using TLS, ensuring that sensitive device information remains secure during transit. This setup supports scalable communication from hundreds or thousands of distributed agents without compromising performance or privacy.

### Cloud Storage and Time-Series Analytics

Once transmitted, data is processed and stored in InfluxDB, a high-performance, time-series database optimised for large-scale IoT data ingestion. This backend

supports rapid querying, aggregation, and long-term retention of component-level data, which is critical for evaluating historical trends and enabling future predictive maintenance features.

### Interactive Dashboard and Visual Interface

The system features a web-based dashboard interface that provides real-time visibility into each device's operational state, as shown in Fig. 2. IT asset manager can access:

- Filterable and customisable visualisations
- Anomaly alerts
- Device-level usage trends
- Comparative component health insights



Fig. 2. Illustrative Dashboard Displaying System Resource Usage Metrics

The dashboard is designed in line with visual analytics best practices to ensure that complex technical data is presented in a clear, actionable format for both IT professionals and non-technical stakeholders.

### Tool Functionality and Key Features

Bringing these elements together, Circul8 provides a robust and user-friendly monitoring experience with several standout capabilities:

- Real-time data capture for CPU, memory, disk, and battery.
- Configurable parameters for threshold alerts and data capture intervals.
- Encrypted MQTT-based communication with auto-recovery and fault tolerance.
- Local processing for validation and early anomaly detection.
- Silent, background operation that ensures minimal user disruption.

This integrated functionality ensures that Circul8 operates reliably in production environments while providing the necessary transparency to inform circularity decisions.

### System Robustness and Challenges Addressed

When developing Circul8, we paid close attention to ensuring it would run smoothly without slowing down users' devices. To keep things lightweight and energy-efficient, we designed the system only to upload essential data rather than constantly syncing everything. This helps reduce latency and keeps performance fast, even on older machines. We also built smart features to help the system automatically bounce back if the connection drops. This means users don't have to restart the app or worry about losing progress—it just picks up where it left off.

Another key focus was ensuring the system could handle messy data—like missing or inconsistent information from sensors—without crashing or producing errors. These decisions help make Circul8 stable and reliable, whether it's being used on a single laptop or rolled out across a whole organisation.

### IV. Deployment Insights and Case Studies

Circul8 was deployed across approximately 70 enterprise laptops and workstations between January 2024 and February 2025 to evaluate its real-world performance within Techbuyer. Devices included a mix of HP, Dell, and Lenovo models used across roles such as office administration, warehouse operations, and hardware

refurbishment. This variety allowed the team to assess the monitoring agent's performance under different workloads and usage contexts. The platform collected high-frequency telemetry (every 3 seconds, with 15-second rolling averages) from core system components, including CPU, memory, disk, and battery. It ran continuously in the background with minimal resource impact—CPU usage remained below 3%, and RAM consumption stayed under 100MB—demonstrating the system's lightweight architecture even on older hardware.

Key insights from the deployment included:

- **Thermal anomalies:** 15% of devices regularly recorded CPU temperatures above 85°C, even during low to moderate workloads. Clustering analysis using K-Means identified these as “Critical” devices, often pointing to fan failures or poor heat dissipation. For example, device HGT-LP227 was categorised as Critical on 98.91% of recorded days.
- **Proactive maintenance actions:** In one case, consistent overheating detected by Circul8 led to the identification and replacement of a faulty cooling fan. This helped restore normal thermal performance and avoided a potential hardware failure.
- **Health trend monitoring:** One of the devices showed persistently low performance, which informed lifecycle decisions such as decommissioning or reallocation.
- **Real-world performance outlining:** The clustering of telemetry data helped segment devices into Healthy, Degraded, and Critical categories, enabling the IT team to prioritise intervention and resource allocation.

This deployment validated Circul8's ability to collect and analyse telemetry efficiently and demonstrated its practical value in supporting timely maintenance, reducing downtime, and extending device usability. These outcomes contribute directly to more sustainable IT practices by delaying unnecessary replacements and reducing electronic waste.

### C. Open-Source release

In line with open innovation and co-creation principles, the Circul8 monitoring agent was released as an open-source tool, published under the MIT License and made publicly available on [GitHub](#). Developed in C#, to be modular, lightweight, and adaptable, the agent can operate across various laptop hardware and usage contexts.

## V. Conclusion

This paper presented the design, development, and real-world deployment of Circul8, a real-time, component-level monitoring tool that supports circular economy (CE) principles in IT asset management. By providing detailed visibility into the health and performance of individual laptop components, Circul8 addresses a significant gap in current sustainability efforts within the ICT sector: the lack of actionable, data-driven insights to guide refurbishment, reuse, and proactive maintenance decisions. The platform features a modular architecture with a lightweight monitoring agent, secure MQTT-based communication, time-series cloud analytics, and an interactive dashboard. This design demonstrates that scalable, privacy-conscious CE application monitoring is technically feasible and operationally valuable. The system deployment across 70 laptops in an organisational setting revealed several

instances where early detection of anomalies enabled timely interventions, thereby preventing unnecessary device replacements and aligning with CE goals. Furthermore, releasing the Circul8 agent as an open-source tool reflects a commitment to openness, transparency, and community-led innovation in sustainable digital infrastructure. This research work's findings provide a technical contribution and a practical pathway for embedding CE thinking into everyday IT operations. By equipping organisations with the ability to make informed decisions about their digital assets, Circul8 transitions from theoretical sustainability frameworks to an implementable, measurable impact.

## VI. Future Work

Building on the solid technical and conceptual foundation established by Circul8, several promising avenues for future research and system enhancement have emerged:

**Health Score and Predictive Modelling:** The current version of Circul8's real-time telemetry pipeline captures the time-series data necessary for predictive modelling. We have piloted health scoring and clustering techniques to identify early signs of degradation, which helps estimate assets' Remaining Useful Life (RUL). Future developments will integrate machine learning models into the existing Node-RED and InfluxDB architecture, allowing us to generate actionable insights. This will transform Circul8 into a comprehensive decision-support system (DSS) for refurbishment, valuation, and lifecycle planning.

**User Nudging and Behavioral Analytics:** Upcoming development phases will introduce a nudging engine to influence user behaviours related to device care, such as managing battery cycles or preventing thermal stress. These context-aware prompts will be delivered non-intrusively via the dashboard or desktop environment, promoting more sustainable device usage without undermining user autonomy.

**User Survey and Feedback Loop:** To inform the design of the nudging module, a perception survey will be conducted to understand users' attitudes toward sustainability prompts, their behavioural tendencies, and their interface preferences. This feedback loop will ensure that behavioural recommendations are relevant, respectful, and grounded in user needs.

**Cross-Platform Expansion:** To broaden the system's institutional applicability, the development will extend the Circul8 agent to support macOS and Linux environments. This expansion will facilitate deployment in diverse IT ecosystems, such as universities, government agencies, and hybrid enterprise environments.

**Longitudinal Impact Assessment:** A follow-up study is planned to evaluate Circul8's environmental and economic impact over time. Key metrics will include avoided hardware replacements, extended device lifespans, and reductions in CO<sub>2</sub> emissions. These findings will help quantify the platform's long-term value proposition and build a robust case for widespread adoption.

In summary, Circul8 lays the groundwork for a new class of intelligent, sustainable IT tools that monitor and actively guide the circular use of digital infrastructure. Combining real-time data, predictive analytics, and user-focused design represents a significant step toward making

circularity operational, measurable, and scalable in the ICT sector.

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#### REFERENCES

- [1] L. Belkhir and A. Elmehri, "Assessing ICT global emissions footprint: Trends to 2040 & recommendations," *Journal of Cleaner Production*, vol. 177, pp. 448-463, 2018/03/10/ 2018, doi: <https://doi.org/10.1016/j.jclepro.2017.12.239>.
- [2] E. Kastanaki and A. Giannis, "Dynamic estimation of future obsolete laptop flows and embedded critical raw materials: The case study of Greece," *Waste Management*, vol. 132, pp. 74-85, 2021/08/01/ 2021, doi: <https://doi.org/10.1016/j.wasman.2021.07.017>.
- [3] A. Rashid, F. M. Asif, P. Krajnik, and C. M. Nicolescu, "Resource conservative manufacturing: An essential change in business and technology paradigm for sustainable manufacturing," *Journal of Cleaner production*, vol. 57, pp. 166-177, 2013.
- [4] N. Ovidiu, G. Mirceaast, and M. Novac, "Data Loss Rate versus Mean Time To Failure in Memory Hierarchies," Dordrecht, 2006: Springer Netherlands, in *Advances in Systems, Computing Sciences and Software Engineering*, pp. 305-307.
- [5] J. S. Mboli, D. Thakker, and J. L. Mishra, "An Internet of Things-enabled decision support system for circular economy business model," *Software: Practice and Experience*, vol. 52, no. 3, pp. 772-787, 2022.
- [6] F. Ahmad, A. Bask, S. Laari, and C. V. Robinson, "Business management perspectives on the circular economy: Present state and future directions," *Technological Forecasting and Social Change*, vol. 187, p. 122182, 2023.
- [7] S. Dinda, "A circular economy approach for sustainable economic development," *International Journal of Green Economics*, vol. 14, no. 2, pp. 174-189, 2020.
- [8] R. Meinhold, C. Wagner, and B. K. Dhar, "Digital sustainability and eco-environmental sustainability: A review of emerging technologies, resource challenges, and policy implications," *Sustainable Development*, 2024.
- [9] A. L. Srivastav *et al.*, "Concepts of circular economy for sustainable management of electronic wastes: challenges and management options," *Environmental Science and Pollution Research*, vol. 30, no. 17, pp. 48654-48675, 2023.
- [10] V. Forti, C. P. Balde, R. Kuehr, and G. Bel, "The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential," 2020.
- [11] K. McMahon, R. Mugge, and E. J. Hultink, "Overcoming barriers to circularity for internal ICT management in organizations: A change management approach," *Resources, Conservation and Recycling*, vol. 205, p. 107568, 2024.
- [12] A. H. Trevisan, A. Lobo, D. Guzzo, L. A. de Vasconcelos Gomes, and J. Mascarenhas, "Barriers to employing digital technologies for a circular economy: A multi-level perspective," *Journal of Environmental Management*, vol. 332, p. 117437, 2023.
- [13] A. P. Valenturf and P. Purnell, "Principles for a sustainable circular economy," *Sustainable production and consumption*, vol. 27, pp. 1437-1457, 2021.
- [14] D. Sumter, J. de Koning, C. Bakker, and R. Balkenende, "Circular economy competencies for design," *Sustainability*, vol. 12, no. 4, p. 1561, 2020.
- [15] M. C. Den Hollander, C. A. Bakker, and E. J. Hultink, "Product design in a circular economy: Development of a typology of key concepts and terms," *Journal of Industrial Ecology*, vol. 21, no. 3, pp. 517-525, 2017.
- [16] E. MacArthur, K. Zumwinkel, and M. R. Stuchtey, "Growth within: a circular economy vision for a competitive Europe," *Ellen MacArthur Foundation*, vol. 100, 2015.
- [17] M. Sesana *et al.*, "Advancing Sustainability and Circularity in the Automotive Industry: A Data-Driven Platform Approach," in *2024 Electronics Goes Green 2024+(EGG)*, 2024: IEEE, pp. 1-11.
- [18] M. Compagnoni, "Is Extended Producer Responsibility living up to expectations? A systematic literature review focusing on electronic waste," *Journal of Cleaner Production*, vol. 367, p. 133101, 2022.
- [19] X. Tong, T. Wang, J. Li, and X. Wang, "Extended producer responsibility to reconstruct the circular value chain," *Circular Economy*, vol. 3, no. 1, p. 100076, 2024.
- [20] N. Mathur, N. Last, and K. Morris, "A process model representation of the end-of-life phase of a product in a circular economy to identify standards needs," *Frontiers in Manufacturing Technology*, vol. 3, p. 988073, 2023.
- [21] K. McMahon, C. Uchendu, and C. Fitzpatrick, "Characterizing IT asset disposition flows for the circular economy: A case study on export for reuse from Ireland," *Journal of Industrial Ecology*, vol. 27, no. 4, pp. 1212-1222, 2023.
- [22] E. Jang, M. Johnson, E. Burnell, and K. Heimerl, "Unplanned Obsolescence: Hardware and Software After Collapse," presented at the Proceedings of the 2017 Workshop on Computing Within Limits, Santa Barbara, California, USA, 2017. [Online]. Available: <https://doi.org/10.1145/3080556.3080566>.
- [23] M. T. Dulman and S. M. Gupta, "Evaluation of maintenance and EOL operation performance of sensor-embedded laptops," *Logistics*, vol. 2, no. 1, p. 3, 2018.
- [24] A. S. George and T. Baskar, "Repairing the Future: The Global Fight for Accessible Fixes and Sustainable Tech," *Partners Universal Innovative Research Publication*, vol. 2, no. 2, pp. 71-88, 2024.
- [25] S. Svensson, J. L. Richter, E. Maitre-Ekern, T. Pihlajarinne, A. Maigret, and C. Dalhammar, "The emerging 'Right to repair' legislation in the EU and the US," in *Going Green CARE INNOVATION 2018*, 2018.
- [26] N. Terzioğlu, "Repair motivation and barriers model: Investigating user perspectives related to product repair towards a circular economy," *Journal of Cleaner Production*, vol. 289, p. 125644, 2021.
- [27] R. Pincirolì, L. Yang, J. Alter, and E. Smirni, "Lifespan and failures of SSDs and HDDs: Similarities, differences, and prediction models," *IEEE Transactions on Dependable and Secure Computing*, 2021.
- [28] M. Mołęda, B. Małysiak-Mrozek, W. Ding, V. Sunderam, and D. Mrozek, "From corrective to predictive maintenance—A review of maintenance approaches for the power industry," *Sensors*, vol. 23, no. 13, p. 5970, 2023.
- [29] A. Sheikh, S. J. Simske, and E. K. P. Chong, "Evaluating Artificial Intelligence Models for Resource Allocation in Circular Economy Digital Marketplace," *Sustainability*, vol. 16, no. 23, p. 10601, 2024. [Online]. Available: <https://www.mdpi.com/2071-1050/16/23/10601>.
- [30] C. P. Baldé *et al.*, "The global e-waste monitor," *United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Geneva/Bonn*, pp. 1-147, 2024.